

Discovery of Two New Accreting Pulsating White Dwarf Stars

Anjum S. Mukadam^{1,2,3}, B. T. Gänsicke⁴, P. Szkody^{1,2}, A. Aungwerojwit^{4,5}, Steve B. Howell^{6,7}, O. J. Fraser^{1,2}, and N. M. Silvestri^{1,2}

ABSTRACT

We report the discovery of two new accreting pulsating white dwarf stars amongst the cataclysmic variables of the Sloan Digital Sky Survey: SDSS J074531.91+453829.5 and SDSS J091945.10+085710.0. We observe high amplitude non-sinusoidal variations of 4.5–7% at a period close to 1230 s in the optical light curves of SDSS J074531.91+453829.5 and a low amplitude variation of 0.7–1.6% near 260 s in the light curves of SDSS J091945.10+085710.0. We infer that these optical variations are a consequence of nonradial g-mode pulsations in the accreting primary white dwarfs of these cataclysmic variables. However we cannot rule out the remote possibility that the 260 s period could be the spin period of the accreting white dwarf SDSS J091945.10+085710.0. We also uncovered a non-variable SDSS J171145.08+301320.0 during our search; our two observing runs exclude any pulsation related periodicities in the range of 85–1400 s with an amplitude $\geq 0.5\%$. This discovery paper brings the total number of known accreting white dwarf pulsators to eleven.

Subject headings: novae, cataclysmic variables—stars:oscillations—stars: variables: other—white dwarfs—stars: individual(SDSS J074531.91+453829.5, SDSS J091945.10+085710.0, SDSS J171145.08+301320.0)

¹Department of Astronomy, University of Washington, Seattle, WA - 98195-1580, USA

²Hubble fellow; anjum@astro.washington.edu

³Visiting Astronomer, Apache Point Observatory, which is owned and operated by the Astrophysical Research Consortium

⁴Department of Physics, University of Warwick, Coventry, CV4 7AL, UK

⁵Department of Physics, Faculty of Science, Naresuan University, Phitsanulok, 65000, Thailand

⁶WIYN Observatory and National Optical Astronomy Observatory, 950 North Cherry Avenue, Tucson, AZ - 85719, USA

⁷Visiting Astronomer, Kitt Peak National Observatory, National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation. The WIYN Observatory is a joint facility of the University of Wisconsin-Madison, Indiana University, Yale University, and the National Optical Astronomy Observatories.

1. Introduction

Cataclysmic variables (CVs) are close binary systems in which a late-type star (secondary) fills its Roche lobe and transfers mass through the inner Lagrangian point to a white dwarf (primary). GW Librae was the first CV discovered with an accreting white dwarf showing photometric variations consistent with nonradial g-mode pulsations observed in non-interacting white dwarf stars (Warner & van Zyl 1998; van Zyl et al. 2000, 2004). This discovery has opened a new venue of opportunity for us to learn about the stellar parameters of accreting variable white dwarfs using asteroseismic techniques. We can probe the insides of a white dwarf using asteroseismology just like seismologists on Earth can learn about the interior of our planet using earthquakes. A unique model fit to the observed periods of the variable white dwarf can reveal information about the stellar mass, core composition, age, rotation rate, magnetic field strength, and distance (see the review paper Winget 1998). This information could prove vital in determining the system dimensions and parameters, and may be the only way to derive conclusive results for non-eclipsing CVs. Pulsating white dwarfs in CVs are also interesting to the variable white dwarf community because they can help establish the effect of accretion on pulsations.

We report new accreting pulsators, SDSS J074531.91+453829.5 and SDSS J091945.10+085710.0 (hereafter SDSS 0745+4538 & SDSS 0919+0857), originally discovered to be CVs in the Sloan Digital Sky Survey (SDSS) by Szkody et al. (2006) and Szkody et al. (2005) respectively. This result comes from our long-term search to discover additional accreting pulsating white dwarf stars in CVs. There are now eleven accreting pulsating white dwarfs known, including the two presented in this paper (see van Zyl et al. 2004; Woudt & Warner 2004; Warner & Woudt 2004; Patterson et al. 2005a,b; Vanlandingham et al. 2005; Araujo-Betancor et al. 2005; Gänsicke et al. 2006; Nilsson et al. 2006). Our goal is to establish the pulsationally unstable region(s) for accreting white dwarfs, which requires a statistically significant number of these systems with well-determined temperatures. Finding the non-variables around an instability strip is equally important in determining its boundaries as discovering variables close to its edges. With this context in mind, we also report a non-variable SDSS J171145.08+301320.0 (hereafter SDSS 1711+3013), discovered as a CV by Szkody et al. (2004). We observed the system twice and place useful non-variability limits related to the absence of pulsation in the primary white dwarf.

2. Selection of Candidates

We select those CVs for high-speed photometry whose optical spectra include prominent broad absorption lines from the white dwarf as well as the contaminating narrow emission

features from the accretion disk. The absorption lines indicate that the white dwarf flux dominates the light from the CV. While this is not a *sufficient* criterion for pulsation in the primary white dwarf, these are the only systems where the search is even possible. When the orbital period of a CV is $\sim 80\text{--}90$ min, it is near the evolutionary period minimum and the CV exhibits the smallest rate of mass transfer. Gänsicke et al. (2006) used the optical accretion luminosity to constrain the rate of mass transfer to be greater than $\sim 10^{-13} M_{\odot}/\text{yr}$, while Kolb & Baraffe (1999) and Howell et al. (1997) theoretically compute the rate of mass transfer at the period minimum to be few times $\sim 10^{-11} M_{\odot}/\text{yr}$. We can expect that the low rates of mass transfer allow a larger surface area of the white dwarf to be visible, making CVs near the period minimum ideal candidates to find additional accreting pulsators. Note that the two criteria mentioned here are not independent.

Arras et al. (2006) investigate the temperature range in which models of accreting white dwarfs with a wide range of masses and Helium enrichment from the donor star would be pulsationally unstable. They find a H/HeI instability strip for accreting model white dwarfs with a blue edge near ≤ 12000 K for a $0.6 M_{\odot}$ star. The blue edge shifts to hotter (cooler) temperatures by about 2000 K for a factor of 10 increase (decrease) in gravity; we can expect the blue edge at 14000 K corresponding to $\log g = 9$ and at 10000 K for $\log g = 7$. This theoretical instability strip is similar to the ZZ Ceti instability strip⁷. For accreting model white dwarfs with a high He abundance (> 0.38), Arras et al. (2006) find an additional hotter instability strip at ≈ 15000 K due to HeII ionization. The boundaries of this intermediate instability strip depend on the Helium abundance and the mass of the accreting white dwarf. For a He abundance higher than 0.48, these theoretical instability strips essentially merge. Arras et al. (2006) expect that there are thus two distinct instability strips for accreting model white dwarfs with a He abundance between about 0.38 and 0.48.

Optical spectra do not lead to sufficiently reliable temperatures for the white dwarf due to contamination from the accretion disk. Accurate temperature determination requires ultraviolet spectra (see Szkody et al. 2007) that we do not have. Hence we are unable to impose any additional selection criteria that depend on the temperature of the primary white dwarf, despite the theoretical framework mentioned above. Besides, an empirical instability strip for accreting white dwarfs has not yet been established. There are only five accreting pulsators with well determined temperatures from ultra-violet spectra; GW Librae, SDSS 013132.39-090122.3, SDSS J161033.64-010223.3, and SDSS J220553.98+115553.7

⁷Non-interacting hydrogen atmosphere (DA) white dwarfs are observed to pulsate in a narrow instability strip located within the temperature range 10800–12300 K for $\log g \approx 8$ (Bergeron et al. 1995, 2004; Koester & Allard 2000; Koester & Holberg 2001; Mukadam et al. 2004b; Gianninas et al. 2005), and are also known as the ZZ Ceti stars.

lie within the range 14500–15000 K (Szkody et al. 2002, 2007), while Araujo-Betancor et al. (2005) find the accreting white dwarf pulsator HS 2331+3905 to be at 10500 K.

3. Modeling the SDSS spectra

Although we do not use temperatures from optical spectra to select candidates, we estimated temperatures for the two pulsators and the non-pulsator discovered during our search. In order to establish the white dwarf temperature, the distance to the system, and to constrain the spectral type of the donor star, we model the optical SDSS spectra as the sum of a white dwarf, an accretion disk, and a late-type secondary star. For the white dwarf, we assume a surface gravity of $\log g = 8$, corresponding to a mass of $M_{\text{wd}} \simeq 0.6M_{\odot}$ and a radius of $R_{\text{wd}} = 8.7 \times 10^8$ cm. The contaminating emission from the accretion disk fills in the Balmer absorption from the white dwarf, making it impossible to determine $\log g$ independently. We then compute a grid of pure hydrogen model spectra covering effective temperatures in the range 8000–20000 K using the codes TLUSTY/SYNSPEC (Hubeny & Lanz 1995; Lanz & Hubeny 1995). We model the accretion disk as an isothermal/isobaric slab of hydrogen (Gänsicke et al. 1999). For the donor star, we use the M-dwarf templates of Beuermann et al. (1998) and L-dwarf templates from Kirkpatrick et al. (1999, 2000). We fix the radius of the secondary star to $R_2 = 8.6 \times 10^9$ cm, which corresponds to a stellar mass of $M_2 = 0.08M_{\odot}$, close to the dividing line between main-sequence and sub-stellar objects, at an orbital period of 80 min.

The free parameters of our three-component model are the white dwarf temperature T_{wd} , the distance d , the spectral type of the secondary star Sp(2), the disc temperature T_{d} , and its surface density Σ_{d} . Considering the number of free parameters, we refrain from applying a formal χ^2 fit and model the SDSS spectrum as follows. We initially calculate a disk spectrum for the given choice of T_{d} and Σ_{d} , and scale the H α emission line fluxes of the model to the observed value. Next, for the chosen T_{wd} , we adjust d to reproduce the observed flux, and judge the goodness of the fit by eye. We ensure that the combination of the white dwarf and the disk fits the Balmer absorption lines in the SDSS spectrum, as well as the slope of the continuum at $\lambda < 5000$ Å, where the contribution of the donor star can safely be ignored. Finally, we scale the selected M/L dwarf template for d as determined from the white dwarf fit. The absence of noticeable TiO bands in the SDSS spectrum provides an *early* limit on the spectral type of the donor – *later* spectral types cannot be excluded. We list the parameters corresponding to our model fits to the SDSS spectra in Table 1, and show these models along with the observed spectra in Figure 1. The white dwarf temperatures estimated from the optical spectra are uncertain by ± 1000 –2000 K.

Table 1. Estimated system parameters for SDSS 0745+4538, SDSS 0919+0857, and SDSS 1711+3013 determined from a three-component (white dwarf, accretion disk, donor star) model fit to their optical SDSS spectra.

CV	T_{wd} [K]	Sp(2)	d [pc]	T_{d} [K]	Σ_{d} [g cm^{-2}]
SDSS 0745+4538	11000	>M8	280	6600	1.7×10^{-2}
SDSS 0919+0857	13000	>M9	235	6300	1.5×10^{-2}
SDSS 1711+3013	10500	>M8	480	6500	1.4×10^{-2}

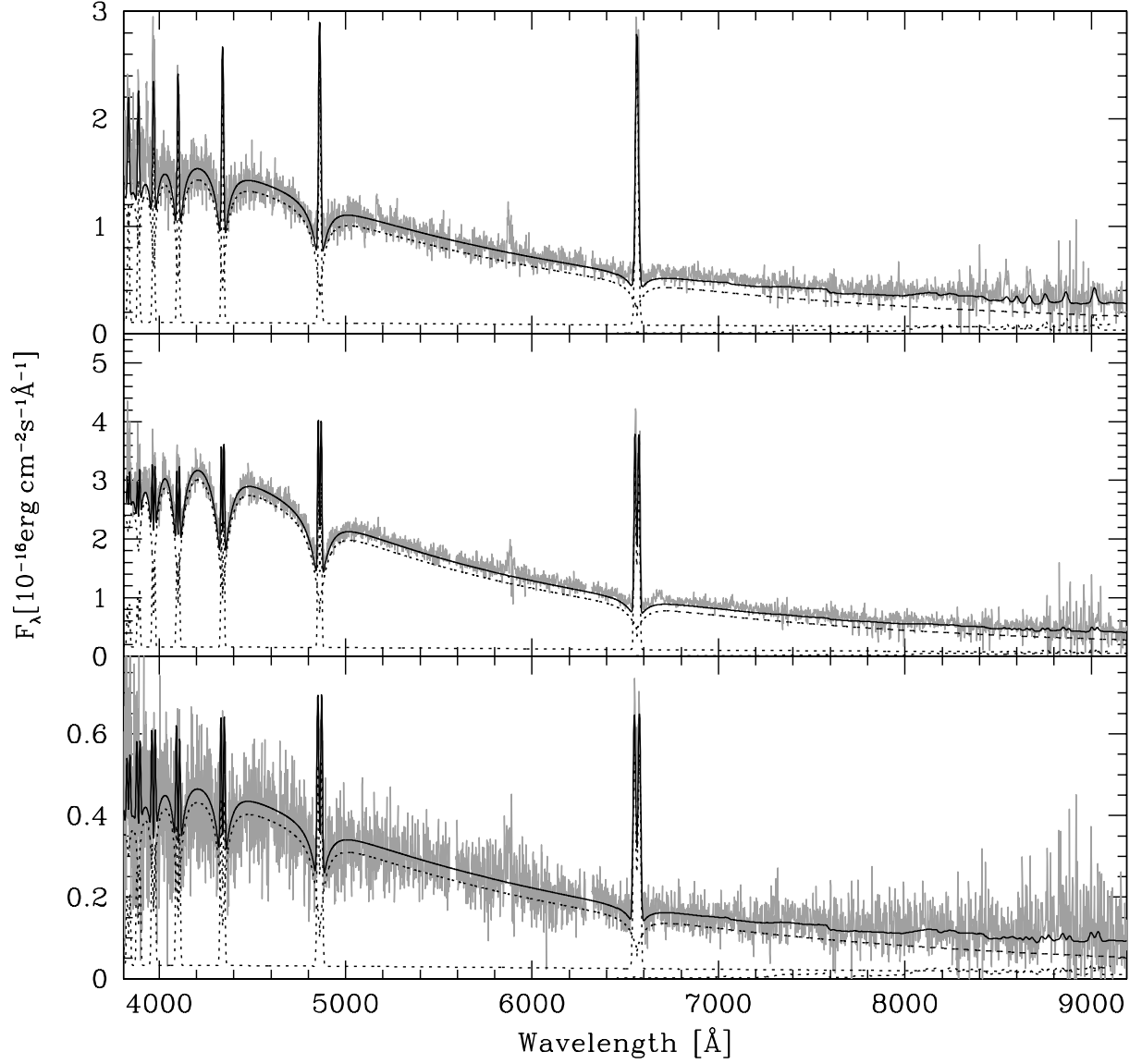


Fig. 1.— We show the observed optical spectra of SDSS0745+4538 (top panel), SDSS0919+0857 (middle panel), and SDSS1711+3013 (bottom panel) in gray along with their respective model fits (black lines) that include three components (dotted lines): primary white dwarf, accretion disk with emission lines, and the secondary star.

The parameters of all three systems discussed here are similar to those of HS 2331+3905 (Araujo-Betancor et al. 2005), SDSS 1339+4847 (Gänsicke et al. 2006), and SDSS 1035+0551 (Southworth et al. 2006), which were analyzed in a similar fashion, i.e. white dwarf temperatures in the range 10500–13000 K, donor stars later than M8, disk temperatures around 6500 K, and surface densities of a few $10^{-2} \text{ g cm}^{-2}$. Follow-up observations of SDSS 1035+0551 revealed eclipses in the light curve, confirming the existence of a brown dwarf donor with $0.052 \pm 0.002 M_{\odot}$ (Littlefair et al. 2006). The limits on the spectral types determined from the SDSS spectra suggest that a substantial fraction of these objects could harbor brown dwarf secondary stars.

4. Observations and Data Reduction

We obtained optical high-speed time-series photometry on suitable SDSS CVs using the 3.5 m telescope at Apache Point Observatory (APO) in New Mexico, the 2.2 m telescope at Calar Alto Observatory (CAO) in Spain, and the 3.5 m WIYN telescope at Kitt Peak National Observatory in Arizona.

We used the Dual Imaging Spectrograph (DIS) in imaging mode, mounted at the Nasmyth focus of the 3.5 m telescope at APO. The instrument design utilizes a dichroic that splits the beam of white light at 555 nm. The blue and red portions of the beam are then incident on two different CCD cameras. We present filterless light curves obtained using the blue CCD camera in this paper, sensitive in the wavelength range 350–555 nm. The instrument has a read noise of about 4.6 electrons RMS, a gain of 1.75 e/ADU, and a plate scale of 0.4 arcsec/pixel at the 3.5 m telescope at APO. We used windowing to read a small portion of the CCD in order to reduce the read time to 2–4 s. Including an additional overhead of 5 s from CCD flushing, writing data to disk, and other software delays, we obtained a dead time of order 7–9 s between exposures. We used a standard IRAF reduction to extract sky-subtracted light curves from the CCD frames using weighted circular aperture photometry (O’Donoghue et al. 2000).

At the 2.2 m CAO telescope, we used the Calar Alto Faint Object Spectrograph (CAFOS) to obtain filterless CCD photometry. We used windowing and binning in order to reduce the read time and hence the dead time between exposures. We applied a bias correction and flat-fielded the images within MIDAS, and then used the Source-extractor algorithm (Bertin & Arnouts 1996) to perform aperture photometry on all objects in the field-of-view and determined corresponding light curves.

We obtained the photometric observations at the WIYN 3.5 m telescope using the Or-

thogonal Parallel Transfer Imaging camera (OPTIC), the prototype orthogonal transfer CCD imager (Tonry et al. 2002). It consists of two 2K x 4K orthogonal transfer CCDs mounted together in a single dewar. The camera has a read noise of <4 electrons RMS, a gain of 1.45 e/ADU, and a plate scale of 0.12 arcsec/pixel at the WIYN 3.5 m telescope. We used OPTIC in conventional mode (see Howell et al. 2003) and all the time-series images were binned 2x2, providing an 8 s readout time between successive exposures. We observed through a blue bandpass BG-39 filter ($\sim B+V$) for our observations. We reduced all the data from the WIYN telescope in exactly the same manner as the APO data.

Although the existing instruments at all the telescopes mentioned above allow short integration times, they are not entirely suitable to study pulsating white dwarfs because they include a substantial dead time between exposures. An ideal instrument such as a blue-sensitive frame transfer CCD camera would not only allow short exposure times, but also include insignificant dead times between consecutive exposures, to enable data acquisition with high time resolution. We indicate our journal of observations acquired at the three different telescopes in Table 2.

After extracting the light curves, we divided the light curve of the target star with a sum of one or more comparison stars; we used brighter stars for the division whenever available as their light curves have lower noise. After this preliminary reduction, we brought the data to the same fractional amplitude scale ($\Delta I/I$) and converted the mid-exposure times of the CCD images to Barycentric Coordinated Time (TCB; Standish 1998). We then computed a Discrete Fourier Transform (DFT) for all the light curves up to the Nyquist frequency.

5. New accreting pulsating white dwarf SDSS 0745+4538

We estimate an effective temperature of 11000 K for the accreting primary white dwarf in SDSS 0745+4538 ($g = 19.05$) using its optical SDSS spectrum and assuming $\log g = 8$ (see Table 1). We show the optical light curves and corresponding DFTs of SDSS 0745+4538 data obtained at the 3.5 m telescope at APO and the 2.2 m telescope at CAO in Figure 2. We indicate the periodicities observed on individual nights in Table 3.

5.1. Orbital Period

The longest g-mode pulsation period observed in cool non-interacting pulsating white dwarfs is ~ 1400 s. Hence we expect that the photometric variations in the light curves with periods longer than 40 min are indicative of the orbital period. The 43.2 min period observed

Table 2. Journal of Observations

Telescope	Object	Start Time (UTC)	Duration (hr)	Exposure (s)
APO 3.5 m	SDSS 0745+4538	14 Oct 2005 11:29:10.458	0.83	15
APO 3.5 m	SDSS 0745+4538	30 Nov 2005 08:03:16.534	2.13	15
APO 3.5 m	SDSS 0919+0857	01 Dec 2005 10:47:54.323	2.17	15
APO 3.5 m	SDSS 0919+0857	05 Dec 2005 10:40:26.316	2.17	15
CAO 2.2 m	SDSS 0745+4538	20 Jan 2006 23:18:54.403	3.83	25
CAO 2.2 m	SDSS 0745+4538	21 Jan 2006 21:12:25.027	3.35	25
CAO 2.2 m	SDSS 0745+4538	22 Jan 2006 20:03:04.435	0.86	35
CAO 2.2 m	SDSS 0745+4538	23 Jan 2006 21:00:57.629	3.56	30
CAO 2.2 m	SDSS 0919+0857	24 Jan 2006 03:26:17.578	2.95	30
APO 3.5 m	SDSS 0745+4538	30 Jan 2006 03:21:42.044	2.14	15
APO 3.5 m	SDSS 0919+0857	20 Feb 2006 03:16:44.490	3.80	15
WIYN 3.5 m	SDSS 1711+3013	29 May 2006 08:44:06.79	2.50	25
WIYN 3.5 m	SDSS 1711+3013	30 May 2006 07:12:25.10	3.21	25
APO 3.5 m	SDSS 0919+0857	16 Mar 2007 06:05:39.243	0.85	15
APO 3.5 m	SDSS 0919+0857	18 Mar 2007 02:08:02.664	3.81	10

on the 30th of January 2006 is merely a harmonic of the 86.5 min period observed on the 20th of January 2006. Using a weighted average of both these periodicities, where the weights are inversely proportional to the 1σ uncertainties, we determine the longest observed period to be 86.3 ± 2.0 min. As the orbital periods of most of the accreting pulsators fall in the range of 80-90 min, indicative of their low rates of mass transfer (see section 2), we conclude that our measurement of 86.3 ± 2.0 min is the orbital period of SDSS 0745+4538.

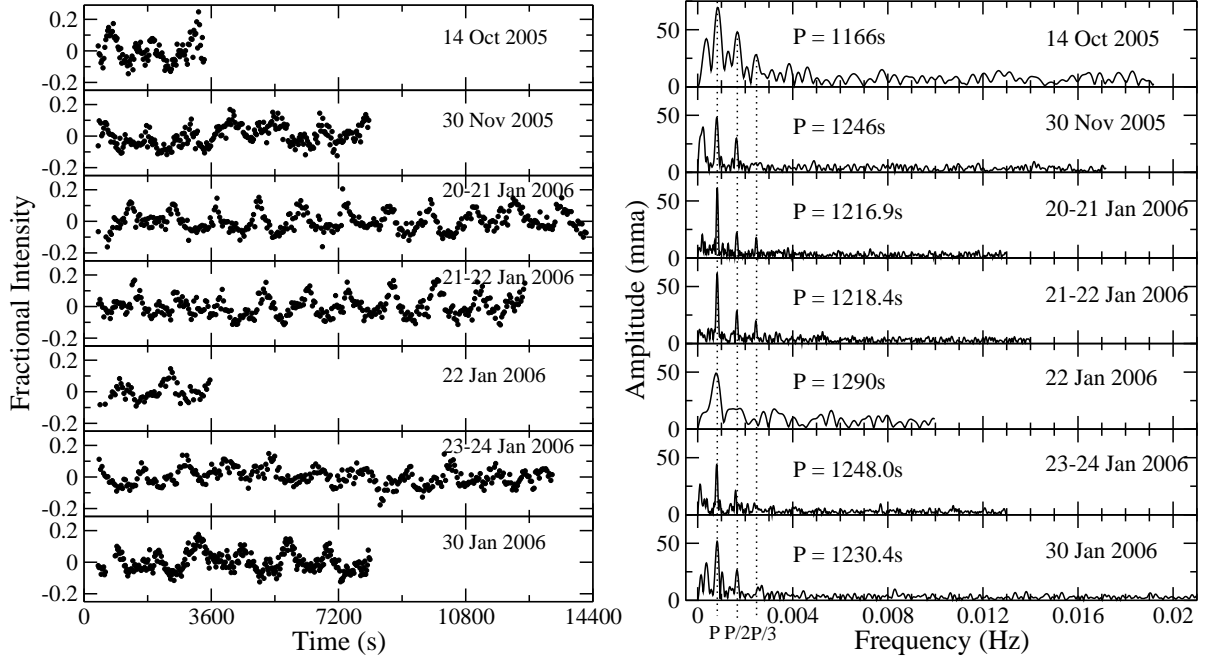


Fig. 2.— Light curves and Discrete Fourier Transforms (DFTs) of SDSS 0745+4538 data obtained using the 3.5 m telescope at Apache Point Observatory and the 2.2 m telescope at Calar-Alto Observatory. We indicate the single pulsation period P observed in each run, along with the first ($P/2$) and second harmonics ($P/3$), indicative of its nonlinear pulse shape.

Table 3. We list all the periodicities observed in the light curves of SDSS 0745+4538. We indicate the single pulsation mode in the accreting white dwarf in boldface and also list the first and second harmonics of this dominant period, whenever present.

Observation Date (UTC)	Orbital Period (min) Amplitude (mma) ^α	Pulsation Period (s); Amplitude (mma) ^α		
		Fundamental P	First Harmonic P/2	Second Harmonic P/3
14 Oct 2005		1166 ± 23; 70.4 ± 6.9	597.4 ± 9.2; 46.8 ± 6.8	
30 Nov 2005		1246 ± 11; 46.1 ± 4.2	613.8 ± 4.1; 28.2 ± 4.3	
20 Jan 2006	86.5 ± 2.3; 20.0 ± 2.7	1216.9 ± 2.7; 60.8 ± 2.7	607.3 ± 1.7; 24.0 ± 2.7	405.4 ± 1.0; 17.1 ± 2.7
21 Jan 2006		1218.4 ± 3.4; 61.1 ± 3.0	609.7 ± 1.8; 28.7 ± 3.0	408.4 ± 1.2; 18.9 ± 3.0
22 Jan 2006		1290 ± 40; 49.4 ± 6.7		
23 Jan 2006		1248.0 ± 4.6; 44.6 ± 3.2	629.4 ± 2.5; 21.0 ± 3.2	418.1 ± 2.1; 11.3 ± 3.2
30 Jan 2006	43.2 ± 0.8; 32.8 ± 3.2 ^β	1230.4 ± 6.4; 54.2 ± 3.2	611.0 ± 3.1; 27.8 ± 3.1	

^αOne milli modulation amplitude (mma) equals 0.1% change in intensity.

^βThe 43.2 min measurement is a harmonic of the orbital period.

5.2. Pulsation Period

We find that all the light curves show a period (P) in the narrow range of 1166–1290 s with a significantly high amplitude. They also show the first harmonic ($P/2$) of this dominant period P , except for the short run on the 22nd of January 2006. We can even see the second harmonic ($P/3$) of this period P in our data on the 20th, 21st, and 23rd of January 2006. We will ignore these harmonics for now as they merely reflect the nonlinear pulse shape of the fundamental mode P , and they are not linearly independent modes. Each light curve of SDSS 0745+4538 therefore shows evidence of a single independent period P besides the orbital period. The value of this dominant independent period P changes from 1166 s to 1290 s, as shown in Table 3. The suggestive lack of stability in the observed period P rules out the possibility that it represents the spin period of the white dwarf. The spin period of a white dwarf in a CV has been shown to be extremely stable, and we expect the rate of change of period with time to be $\dot{P} \leq 10^{-14}$ (Wood et al. 2005; Mauche 2006).

We now consider the possibility that the dominant period P in each of the light curves of SDSS 0745+4538 represents a pulsation mode excited in the primary white dwarf. We find that the observed range of periods 1166–1290 s are consistent with nonradial g-mode pulsations in white dwarf stars. Furthermore we observe high amplitudes in the long period (600–1200 s) ZZ Ceti stars (Clemens 1993; Kanaan et al. 2002; Mukadam et al. 2006), which is also consistent with the observed amplitudes in SDSS 0745+4538. The pulse shapes of the long period ZZ Ceti stars are mostly non-sinusoidal and therefore result in harmonics in the DFTs, which is similar to the behavior shown by SDSS 0745+4538. We also see evidence of large amplitude modulation in the pulsation spectra of long period ZZ Ceti stars even on timescales as short as a few days (e.g. Kleinman et al. 1998); we explain the phenomenon of amplitude modulation below.

The eigenfrequencies of a pulsating white dwarf, representative of its fundamental parameters and stellar structure, change only on evolutionary timescales $\dot{\nu} \sim 10^{-19}$ Hz/s (e.g. Kepler et al. 2005). We can expect that accreting pulsating white dwarfs evolve faster than their isolated counterparts, but we still expect changes in the eigenfrequencies to occur on extremely slow timescales $\dot{\nu} \sim 10^{-12}$ Hz/s (see Townsley et al. 2004). Variable white dwarfs exhibit only a handful of all possible eigenfrequencies at any given time. If new eigenmodes get excited in the star and previously excited eigenmodes are entirely suppressed, then the observed pulsation spectrum will show different frequencies. This does not imply that the eigenfrequencies themselves are changing, but that the amplitude of excitation can vary on short timescales from zero to a finite value. This amplitude modulation explains why we observe a different dominant period P in each of the light curves of SDSS 0745+4538. The behavior of the optical variations in SDSS 0745+4538 is completely consistent with nonradial

white dwarf pulsations.

6. New accreting pulsating white dwarf SDSS 0919+0857

We estimate an effective temperature of 13000 K for SDSS 0919+0857 ($g = 18.2$), uncertain by a few 1000 K (see Table 1). We show the optical light curves and corresponding DFTs of SDSS 0919+0857 acquired using the 3.5 m telescope at APO and the 2.2 m telescope at CAO in Figure 3. We indicate the periods and amplitudes of the optical variations observed on individual nights in Table 4.

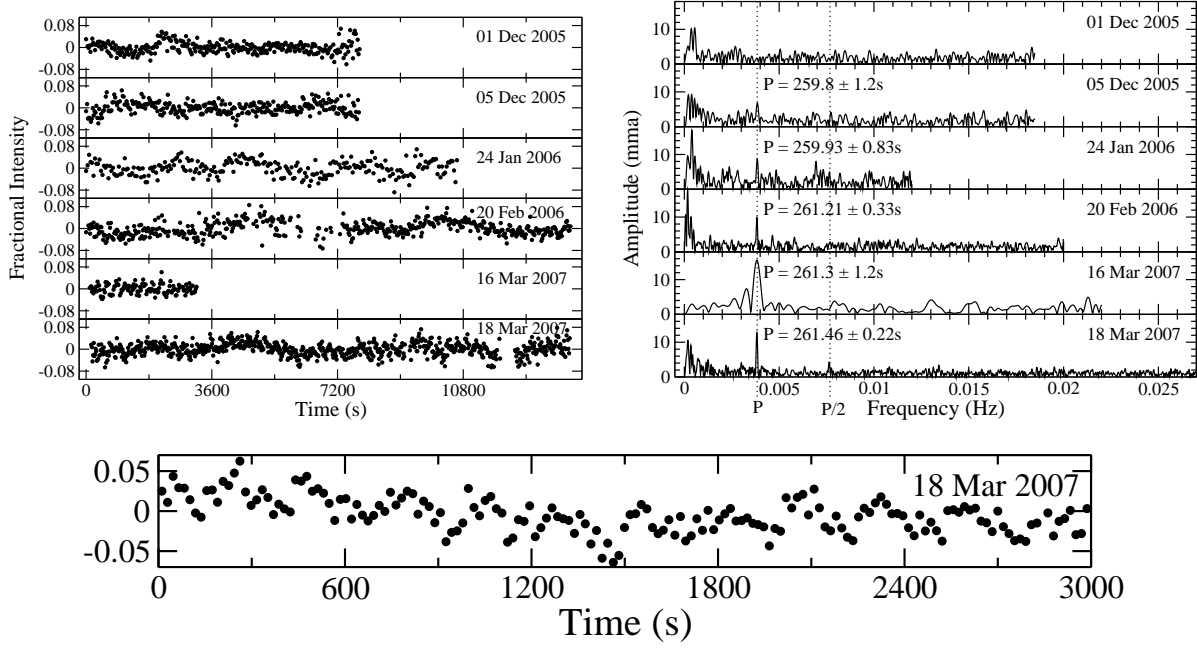


Fig. 3.— Light curves and DFTs of SDSS 0919+0857 data acquired using the 3.5 m telescope at APO and the 2.2 m telescope at CAO. We indicate the location of the period ~ 260 s and its first harmonic ($P/2$) against the DFTs computed for all the runs. Pulsations are clearly evident in the light curve from 18th of March 2007 shown separately.

6.1. Orbital Period

Szkody et al. (2005) determine the orbital period of SDSS 0919+0857 to be 84 ± 8 min from radial velocity measurements. The light curve variations longer than 30 min are all suggestive of being either direct measurements or harmonics of this period. Most of these measurements are consistent with each other, considering that the uncertainties are underestimated. We compute a weighted average for the orbital period to be 90.9 ± 1.8 min, where the weights are inversely proportional to the 1σ uncertainties. We boost the error bar to 7.3 min to make the average value consistent with all the different measurements. This step is necessary to derive a realistic estimate of the uncertainty in measuring the orbital period; the observing runs are too short to determine the orbital period reliably and hence the least squares uncertainties are severely under-estimated. Our determination of the orbital period then becomes 91 ± 7 min, which is about seven minutes longer than the determination of Szkody et al. (2005), but consistent within the uncertainties.

Table 4. We list all the periodicities observed in the light curves of SDSS 0919+0857. We indicate the short period close to 260 s in boldface, that which we deduce to be the nonradial g-mode exhibited by the primary white dwarf.

Observation Date (UTC)	Orbital Period (min); Amplitude (mma)			Pulsation Related Period (s); Amplitude (mma)		
	Fundamental P	First Harmonic P/2	Second Harmonic P/3	Fundamental P	First Harmonic P/2	Linear Combination??
01 Dec 2005		45.1 ± 1.6 ; 9.1 ± 1.6	31.1 ± 0.8 ; 8.6 ± 1.5			
05 Dec 2005				259.8 ± 1.2 ; 6.8 ± 1.7		
24 Jan 2006		41.8 ± 0.7 ; 17.0 ± 2.0		259.93 ± 0.83 ; 8.6 ± 2.0		144.09 ± 0.27 ; $8.0 \pm 2.0^\gamma$
20 Feb 2006	94.5 ± 1.4 ; 18.6 ± 1.2	47.0 ± 0.5 ; 12.1 ± 1.2		261.21 ± 0.33 ; 9.6 ± 1.2		
16 Mar 2007				261.3 ± 1.2 ; 15.8 ± 1.6		
18 Mar 2007	88.2 ± 1.6 ; 11.4 ± 1.0	48.8 ± 0.6 ; 9.7 ± 1.0		261.46 ± 0.22 ; 12.7 ± 1.0	130.93 ± 0.17 ; 4.2 ± 1.0	

$^\gamma$ This period is only a 2.5σ detection.

6.2. Pulsation Period

All, but one, of the light curves indicate a short period P near 260 s, as shown in Table 4. Measurements from the 5th of December 2005 and the 24th of January 2006 indicate a value near 259.9 s, while the other measurements indicate a distinct value near 261.3 s. This suggests that the 260 s period is a doublet; sampling different phases of the beat cycle where one mode may dominate over the other can explain the slightly different period measurements. In the short period ZZ Ceti stars (200–300 s) close to the blue edge of the non-interacting ZZ Ceti instability strip, we often observe multiplet structure in the excited modes due to rotation or magnetic field. These stars typically show lower amplitudes in the range of 1–20 mma (Clemens 1993; Kanaan et al. 2002; Mukadam et al. 2006), which is consistent with the amplitudes observed for the 260 s period.

Our present constraint on the splitting of the 260 s mode is about $20.6 \mu\text{Hz}$. If the splitting were caused by rotation, this would imply a spin period of ~ 1.8 days, which is too slow for an accreting white dwarf. It is therefore much more likely that the splitting is caused by a magnetic field $\sim 10^5$ G (see Jones et al. 1989). We can justify that the mode was not observed on the 1st of December 2005 due to beating of the closely spaced frequencies. The amplitude modulation from 6.8 mma⁸ on the 5th of December 2005 to 15.8 mma on the 16th of March 2007 lends support to this idea. Although we find no evidence to contradict our idea that the 260 s period is a nonradial g-mode, we are unable to eliminate the remote possibility that it could be the spin period of the white dwarf.

We expect to measure the spin period of a rapidly rotating white dwarf in a CV whenever there are features on the surface of the white dwarf, such as a hot spot. Such a hot spot typically arises in accreting white dwarfs with a strong magnetic field, where the accretion flow close to the white dwarf becomes field-aligned. The accretion stream then funnels to one or both magnetic poles. The stream undergoes a shock front and radiates X-rays which heat the white dwarf surface near the pole(s). There are two kinds of CVs that show hot spots: Intermediate Polars with magnetic fields of 1–10 MG, usually with some outer accretion disk, and Polars with fields > 15 MG devoid of a disk. Since the optical spectrum of SDSS 0919+0857 shows double-peaked lines, typical of an accretion disk, it is not likely to be a Polar CV. The spectrum does not show any signs of Zeeman splitting, suggesting that the field is smaller than 1 MG (see Wickramasinghe & Ferrario 2000). Also, there is no X-ray source associated with SDSS 0919+0857 (see Szkody et al. 2005, and references therein). These constraints reduce the possibility that SDSS 0919+0857 is an Intermediate Polar, and the 260 s period represents the spin period of the white dwarf caused by a rotating hot

⁸One milli modulation amplitude (mma) equals 0.1% change in intensity.

spot. However we are not completely certain because Araujo-Betancor et al. (2005) claim to observe the spin period of 1.12 min in the recently discovered accreting pulsating white dwarf HS 2331+3905; its optical spectrum does not show any Zeeman splitting and it is not associated with any X-ray source either.

We had initially dismissed the 144 s period observed on the 24th of January 2006 as noise due to flickering. But we find that this period is perhaps revealing the interaction of the orbital period with the 260 s period. Let Ω be the frequency associated with the harmonic of the orbital period 41.8 min observed on the 24th of January 2006. Let f_1 and f_2 be the frequencies associated with the 259.93 s and 144.09 s periods respectively. We find that within uncertainties $f_2 = 2(f_1 - \Omega)$. This implies that f_2 could be a linear combination frequency, however its amplitude is only 2.5 times the average noise amplitude, making it less reliable than a 3σ detection. We cannot explain why we do not observe $(f_1 - \Omega)$, and why the 144 s period is only visible during one set of observations, if it is indeed real. This does not help us resolve the dilemma of whether the 260 s period represents the spin period or a pulsation mode, as both these phenomena could potentially interact with the orbital period through tides.

Our observations on the 1st of December 2005 do not show the 260 s period inspite of a suitably low noise level (see Figure 3). It is possible that the accretion is clumpy at these low rates of mass transfer. If the accretion stopped for some time, the hot spot could cool off, explaining the absence of the 260 s period during our first run under this scenario. We can explain the observed 260 s period with two different models: nonradial pulsation and rotation. We adopt the model of nonradial pulsation here because it is more likely.

7. Non-variable from our search SDSS 1711+3013

We report a non-variable SDSS 1711+3013 ($g = 20.25$), which we observed twice during our search, obtaining useful non-variability limits related to the absence of pulsations in the primary white dwarf. Note that even CVs that show variability from flickering, spin or orbital period modulations, would still count as non-variables in this context. We show the light curves and DFTs of SDSS 1711+3013 acquired using the WIYN 3.5 m telescope in Figure 4. We indicate the periods and amplitudes of the optical variations related to the orbital period in Table 5.

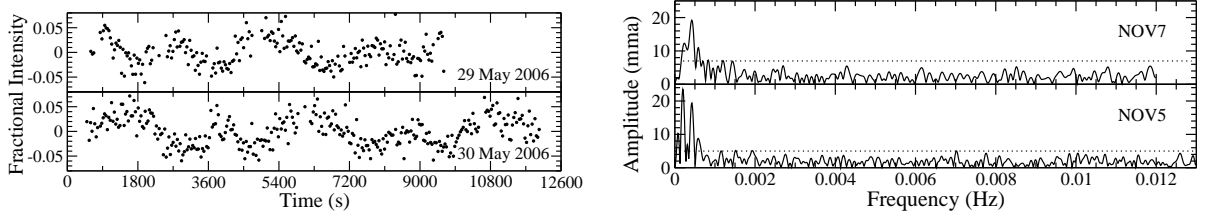


Fig. 4.— We show the light curves and corresponding DFTs of SDSS 1711+3013 data obtained using the 3.5 m WIYN telescope. We also indicate the pulsation related non-variability limit in mma, subsequent to the NOV designation.

Table 5. We list the periods observed in the light curves of SDSS 1711+3013, representative of modulations related to the orbital period. We also list the non-variability limit related to pulsation.

Observation Date (UTC)	Orbital Period (min); Amplitude (mma)		Non-variability Limit for Nonradial Pulsations
	Fundamental P	First Harmonic P/2	
29 May 2006		39.4 ± 0.7 ; 18.1 ± 2.1	≤ 7 mma for periods within 83–1430 s (NOV7)
30 May 2006	83.3 ± 1.7 ; 22.0 ± 1.6	38.8 ± 0.4 ; 18.5 ± 1.6	≤ 5 mma for periods within 77–1470 s (NOV5)

7.1. Orbital Period

The DFT of SDSS 1711+3013 acquired on the 29th of May 2006 exhibits substantial power at low frequencies, and we fit the highest unresolved peak to determine the harmonic of the orbital period ≈ 39.4 min. The light curve from the next night distinctly shows both the orbital period and its harmonic at 83.3 min & 38.8 min respectively. Our weighted average of these three measurements is 78.8 ± 1.4 min, using weights that are inversely proportional to the 1σ uncertainties. We artificially boost the error bar to 4.5 min for consistency with all the measurements. Hence our determination of the orbital period becomes 79 ± 5 min. Note that both light curves from Figure 4 show a distinctive feature: the orbital modulation consists of a ~ 30 – 35 min lower amplitude feature followed by a ~ 50 min relatively higher amplitude feature.

7.2. Pulsation related Non-variability Limit

SDSS 1711+3013 was Not Observed to Vary (NOV), and we designate it as NOV x , where x represents the non-variability limit determined from the DFT, similar to the scheme for non-variables within and around the ZZ Ceti instability strip (see Mukadam et al. 2004a). The highest peak in the DFT essentially defines the detection threshold or the non-variability limit, provided it is not related to the orbital period or also present in the DFTs of the reference stars. In that case, we apply the same test to the second-highest peak, and so on, until we can determine the highest peak, truly representative of the non-variability limit.

The data acquired using the WIYN 3.5 m telescope on the 29th of May 2006 (top right panel, Figure 4) allow us to constrain the pulsation amplitude below 7 mma for periods in the range of 83–1430 s. The data from the 30th of May 2006 (bottom right panel, Figure 4) restrict the pulsation amplitude to below 5 mma for periods in the range of 77–1470 s. We conclude that there are no pulsation related periodicities in the range of about 85–1400 s that are higher than the limiting amplitude of 0.5%; we designate this non-variable as NOV5.

We estimate an effective temperature of 10500 K for the accreting primary white dwarf in SDSS 1711+3013 using its optical SDSS spectrum (see Table 1). Since most of the known accreting white dwarf pulsators cluster in the temperature range of 14500–15000 K (Szkody et al. 2007), we wonder if the non-variable SDSS 1711+3013 is too cool to lie within the instability strip(s) for variable accretors. Araujo-Betancor et al. (2005) determine an effective temperature of 10500 K for the accreting white dwarf pulsator HS 2331+3905. However given the uncertainty of ~ 2000 K in our temperature estimate, SDSS 1711+3013 could easily be substantially cooler than HS 2331+3905.

8. Summary

The light curves of SDSS 0745+4538, SDSS 0919+0857, and SDSS 1711+3013 show optical variations indicative of the orbital period of these binary systems. We determine an orbital period of 86.3 ± 2.0 min for SDSS 0745+4538, 91 ± 7 min for SDSS 0919+0857, and 79 ± 5 min for SDSS 1711+3013 using our data.

We also observe a single independent period in the light curves of SDSS 0745+4538 in the range of 1166–1290 s, which varies from run to run. The spin of the white dwarf is expected to be highly stable and cannot explain the observed variations. We deduce that the variations in the light curves of SDSS 0745+4538 with long periods, high amplitudes of 4.5–7%, non-sinusoidal pulse shapes, and substantial amplitude modulation are completely consistent with nonradial g-modes, similar to those observed for the non-interacting long period cool ZZ Ceti stars.

We observe a persistent period close to 260 s in five out of six of the light curves of SDSS 0919+0857. We adopt the explanation that this period is a nonradial pulsation mode with doublet structure and consequent beating, similar to the modes excited in the short period ZZ Ceti stars. The observed amplitudes are also consistent with the small amplitudes observed in the short period ZZ Ceti stars, found close to the blue edge of the ZZ Ceti instability strip. But we cannot rule out the remote possibility that the 260 s period could be the spin period of the white dwarf without additional data that span a long timebase.

Even after observing SDSS 1711+3013 twice, we did not find any pulsation related periodicities in the range of 85–1400 s that are higher than the limiting amplitude of 0.5% (NOV5). We therefore conclude that SDSS 1711+3013 does not exhibit nonradial pulsations. Our temperature estimate of 10500 K for this accreting white dwarf suggests that it may perhaps be too cool to pulsate. This discovery paper brings the total number of known accreting white dwarf pulsators to eleven.

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REFERENCES

- Araujo-Betancor, S., et al. 2005, *A&A*, 430, 629
- Arras, P., Townsley, D. M., & Bildsten, L. 2006, *ApJ*, 643, L119
- Bergeron, P., Wesemael, F., Lamontagne, R., Fontaine, G., Saffer, R. A., & Allard, N. F. 1995, *ApJ*, 449, 258
- Bergeron, P., Fontaine, G., Billères, M., Boudreault, S., & Green, E. M. 2004, *ApJ*, 600, 404
- Bertin, E., & Arnouts, S. 1996, *A&AS*, 117, 393
- Beuermann, K., Baraffe, I., Kolb, U., & Weichhold, M. 1998, *A&A*, 339, 518
- Clemens, J. C. 1993, Ph.D. Thesis, University of Texas at Austin
- Gänsicke, B. T., Sion, E. M., Beuermann, K., Fabian, D., Cheng, F. H., & Krautter, J. 1999, *A&A*, 347, 178
- Gänsicke, B. T., et al. 2006, *MNRAS*, 365, 969
- Gianninas, A., Bergeron, P., & Fontaine, G. 2005, *ApJ*, 631, 1100
- Howell, S. B., Rappaport, S., & Politano, M. 1997, *MNRAS*, 287, 929
- Howell, S. B., Everett, M. E., Tonry, J. L., Pickles, A., & Dain, C. 2003, *PASP*, 115, 1340
- Hubeny, I., & Lanz, T. 1995, *ApJ*, 439, 875
- Jones, P. W., Hansen, C. J., Pesnell, W. D., & Kawaler, S. D. 1989, *ApJ*, 336, 403
- Kanaan, A., Kepler, S. O., & Winget, D. E. 2002, *A&A*, 389, 896
- Kepler, S. O., et al. 2005, *ApJ*, 634, 1311
- Kirkpatrick, J. D., et al. 1999, *ApJ*, 519, 802
- Kirkpatrick, J. D., et al. 2000, *AJ*, 120, 447
- Kleinman, S. J. et al. 1998, *ApJ*, 495, 424
- Koester, D. & Allard, N. F. 2000, *Baltic Astronomy*, 9, 119
- Koester, D., & Holberg, J. B. 2001, *ASP Conf. Ser.* 226: 12th European Workshop on White Dwarfs, 226, 299

- Kolb, U., & Baraffe, I. 1999, MNRAS, 309, 1034
- Lanz, T., & Hubeny, I. 1995, ApJ, 439, 905
- Littlefair, S. P., Dhillon, V. S., Marsh, T. R., Gänsicke, B. T., Southworth, J., & Watson, C. A. 2006, Science, 314, 1578
- Mauche, C. W. 2006, MNRAS, 369, 1983
- Mukadam, A. S., et al. 2004a, ApJ, 607, 982
- Mukadam, A. S., Winget, D. E., von Hippel, T., Montgomery, M. H., Kepler, S. O., & Costa, A. F. M. 2004b, ApJ, 612, 1052
- Mukadam, A. S., Montgomery, M. H., Winget, D. E., Kepler, S. O., & Clemens, J. C. 2006, ApJ, 640, 956
- Nilsson, R., Uthas, H., Ytre-Eide, M., Solheim, J.-E., & Warner, B. 2006, MNRAS, 370, L56
- O’Donoghue, D., Kanaan, A., Kleinman, S. J., Krzesinski, J., & Pritchett, C. 2000, Baltic Astronomy, 9, 375
- Patterson, J., Thorstensen, J. R., & Kemp, J. 2005a, PASP, 117, 427
- Patterson, J., Thorstensen, J. R., Armstrong, E., Henden, A. A., & Hynes, R. I. 2005b, PASP, 117, 922
- Southworth, J., Gänsicke, B. T., Marsh, T. R., de Martino, D., Hakala, P., Littlefair, S., Rodríguez-Gil, P., & Szkody, P. 2006, MNRAS, 373, 687
- Standish, E. M. 1998, A&A, 336, 381
- Szkody, P., Gänsicke, B. T., Howell, S. B., & Sion, E. M. 2002, ApJ, 575, L79
- Szkody, P., et al. 2004, AJ, 128, 1882
- Szkody, P., et al. 2005, AJ, 129, 2386
- Szkody, P., et al. 2006, AJ, 131, 973
- Szkody, P., et al. 2007, ApJ, accepted
- Tonry, J. L., Luppino, G. A., Kaiser, N., Burke, B. E., & Jacoby, G. H. 2002, Proc. SPIE, 4836, 206

- Townsley, D. M., Arras, P., & Bildsten, L. 2004, *ApJ*, 608, L105
- Vanlandingham, K. M., Schwarz, G. J., & Howell, S. B. 2005, *PASP*, 117, 928
- van Zyl, L., Warner, B., O'Donoghue, D., Sullivan, D., Pritchard, J., & Kemp, J. 2000, *Baltic Astronomy*, 9, 231
- van Zyl, L., et al. 2004, *MNRAS*, 350, 307
- Warner, B., & van Zyl, L. 1998, *IAU Symp.* 185: New Eyes to See Inside the Sun and Stars, 185, 321
- Warner, B., & Woudt, P. A. 2004, *ASP Conf. Ser.* 310: *IAU Colloq.* 193: Variable Stars in the Local Group, 310, 382
- Wickramasinghe, D. T., & Ferrario, L. 2000, *PASP*, 112, 873
- Winget, D. E. 1998, *Journal of Physics: Condensed Matter*, 10, 11247
- Wood, M. A., et al. 2005, *ApJ*, 634, 570
- Woudt, P. A., & Warner, B. 2004, *MNRAS*, 348, 599